# 1V CMOS $G_m$-$C$ Filters

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# 1V CMOS $G_m$-$C$ Filters

## Design and Applications

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# Preface

There are growing demands for low-voltage circuits and systems, especially for system-on-a-chip applications. When switched to low supply voltage, digital circuits do not suffer the degradation in performance. On the other hand, the circuit performance of analog circuits are strongly affected by reduced supply voltage. In addition, chip area should also be taken into consideration to reduce the cost of advanced multi-function SOC design. Therefore, there is urgent need to develop new design techniques for analog circuits at 1-V supply.

In Chapter 2, novel transconductors with the applications for wireless and wireline systems are introduced. The transconductor is a basic building block for analog circuits, such as the $G_m$-$C$ filter, continuous-time delta-sigma modulator, voltage-controlled oscillator, and multiplier. First, the configuration of a linearized transconductor for low-voltage and high-frequency applications is proposed. By using double pseudo-differential pairs and the source degeneration structure under nano-scale CMOS technology, the nonlinearity caused by short channel effect from small feature size can be minimized. Then, another transconductor with pseudo-differential structures is proposed. The linearity is improved by mobility compensation techniques as the device size is scaled down to achieve high-speed operation. Short channel effects in the nano-scale technology are discussed and eliminated, and the results show superior performance even at high-speed operation. Finally, a transconductor with the specific target for ADSL2+ application is discussed. A precise model is adopted to eliminate short channel effects and high linearity performance can thus be achieved.

Chapter 3 focuses on the basic concept of the $G_m$-$C$ implementation. A $G_m$-$C$ filter with a fifth-order Elliptic prototype and a wide tuning range for very low frequency is discussed. The transconductor can work from the weak inversion region to the strong inversion region to maximize the transconductance tuning range. The transconductance can be tuned by changing its bias current. Through the use of switching technology, the filter can be applied to biomedical systems, audio systems and part of wireless systems.

Three multi-mode channel selection filters for the Zero-IF direct conversion receiver are presented in Chapter 4. The specific transconductors with required

functions are designed through the use of a third-order Butterworth prototype. The proposed circuit first uses the forward voltage follower structure and an active resistor to implement the linear transconductor. The wide tuning range would be suitable for the specifications of IEEE 802.11a/b/g Wireless LANs, Wideband CDMA, cdma2000, and Bluetooth. Then, the other transconductor is presented. The transconductor includes a voltage-to-current converter and a current multiplier. Voltage-to-current conversion employs linear-region MOS transistors and the circuit features high linearity over a wide input swing. The current multiplier which operates in the weak inversion region provides a wide transconductance tuning range without degrading the linearity. The tuning range and the linearity performance would be suitable for the wireless specifications of GSM, Bluetooth, cdma2000, and Wideband CDMA. Finally, another transconductor uses the same concept as that of the previous one. Linear-region MOS transistors are employed to perform the voltage-to-current conversion. The wide tuning range can be achieved by the current multiplier following the linear voltage-to-current converter.

Two high-speed filters with a fourth-order equiripple prototype are analyzed in Chapter 5. The high-speed filter can be used for pulse signal systems. One is designed for the hard disk storage systems, and a novel automatic tuning circuit is also implemented to account for variations in process and temperature. A high-speed transconductor with the inverter structure is realized. Transconductance tuning can be achieved by adjusting the bulk voltage using the Deep-NWELL technology. Then, a high-performance $G_m$-$C$ equiripple linear phase low-pass filter for UWB wireless application is presented. The proposed transconductor is designed under low supply voltage while its gain, excess phase, and linearity are well maintained.

This book is organized based upon the Ph.D. dissertation in National Chiao Tung University, Taiwan. It includes details and measurement results for each research project, and the analyses made with circuits operating at 1-V supply. The projects were supported by the National Science Council of Taiwan, while the chips were fabricated by the National Chip Implementation Center of Taiwan.

This book would not been published without the help and kindness of many individuals. First of all, we would like to thank Prof. Mohammed Ismail of the Ohio State University for his helpful comments. He is indeed a world leader in the research and education of analog and RF circuit designs. Some sections are enlightened by his influential work. We would like to express our gratitude to Mr. Chih-Lung Kuo, who has made significant contribution to this book. He spent days and nights typesetting and editing the initial version. A special thank goes to all the members of NCTU Analog Integrated Circuit Lab for their generous assistance and insightful technical discussion over the years. Finally, the first author would like to thank Dr. Hung-Sung Li at MediaTek Inc. for his guidance, encouragement, and support.

*Tien-Yu Lo*
*Chung-Chih Hung*

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# Chapter 1
# Motivation

## 1.1 Introduction

Low-voltage VLSI circuits have received significant attention in recent years. The supply voltage has decreased following the advancement of process technology, and the operation frequency of CMOS can also go up higher than 100 GHz. The demands for nano-scale applications are mainly classified into technology-driven, design-driven, and market-driven. They are mainly to reduce the minimum feature size to scale down the chip area, to fabricate millions of transistors on a single chip to save cost, and to the increase market demands for communication electronic products. These demands seem to be independent of each other. However, the advances in VLSI technology, circuit design, and product market are actually interrelated.

In the past decade, CMOS technology has played a major role in the rapid advancement and the increased integration of VLSI systems. CMOS devices feature high input impedance, extremely low offset switches, high packing density, low switching power consumption, and thus can be easily scaled. The minimum feature size of a MOS transistor has been decreasing [1–3]. Current VLSI technology is scaled down to around 90 nm. Scaling down the transistor sizes can then integrate more circuit components in a single chip, so the circuit area and thus its cost will be reduced. Besides this economic consideration, smaller geometry usually lowers the parasitic capacitance, which leads to higher operating speed. When a MOS transistor size is decreased, not only its channel length and width are reduced, but also the thickness of the gate oxide. As a MOS transistor has a thinner gate oxide, in order to prevent the transistor from breakdown due to higher electrical field across the gate oxide and to ensure its reliability, the supply voltage needs to be reduced [4–8]. Since the digital circuits are becoming more and more popular, the computer-aided design tools for digital circuits are getting matured, the digital circuits are certainly occupying most of the fabricated chip area, and the electrical characteristics of MOS transistors are getting optimized mainly for digital circuits. Switching to use nano-scale devices, digital circuits do not suffer the degradation of their performances too much.

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On the other hand, for analog circuits, the circuit performances, such as gain, dynamic range, speed, bandwidth, linearity, etc., are strongly affected by using nano-scale technology. Therefore, new design techniques for nano-scale analog circuits are required to be developed. Moreover, since we are living in an analog world, it is inevitable to use analog signal processing. Modern analog and mixed-signal VLSI applications in areas such as telecommunications, smart sensors, battery-operated consumer electronics and artificial neural computation require CMOS analog design solutions. Thus, analog signal and information processing in nano-scale technology is really a field requiring more devotion.

## 1.2 Applications

In the systems that interface with real word, the processed signal would be measured with unwanted noise. A filter is usually used to get rid of the unwanted noise and to reject the surrounding interface. Thus, filters are important block for specified frequency of signals and they are essential for many applications. They can be used to band-limit signals in wireline and wireless communication systems. These filters operate on continuous-time fashion because the systems interface with real analog world. Figure 1.1 shows the required low-pass filter for specified applications.

There are two kinds of the filters: digital filters and analog filters. The analog filters process the continuous data rather than the digital data for digital filters. The analog filters can be further divided into passive filters and active filters. The elements of a passive filter are passive, and a passive filter includes resistors, capacitors, inductors, and transformers. On the contrary, the active filters include active devices. A large area is required for the passive filter, and then the active filter is more suitable in CMOS technology.

Active filters can be classified into Active-RC, Switched-Capacitor, $G_m$-$C$, and LC filters. The Active-RC and Switched-Capacitor filters are only suitable for low to medium frequency applications. For high frequencies, the settling problem of

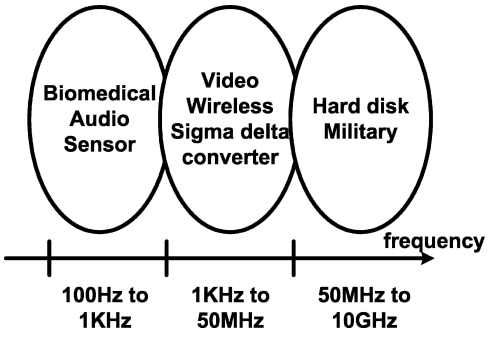


**Fig. 1.1** The filter operation frequency for various applications